Structural Design

The Space Shuttle—a mostly reusable, human-rated launch vehicle, spacecraft, space habitat, laboratory, re-entry vehicle, and aircraft—was an unprecedented structural engineering challenge. The design had to meet several demands, which resulted in innovative solutions. The vehicle needed to be highly reliable for environments that could not be simulated on Earth or fully modeled analytically for combined mechanical and thermal loads. It had to accommodate payloads that were not defined or characterized. It needed to be weight efficient by employing a greater use of advanced composite materials, and it had to rely on fracture mechanics for design with acceptable life requirements. It also had to be certified to meet strength and life requirements by innovative methods. During the Space Shuttle Program, many such structural design innovations were developed and extended to vehicle processing from flight to flight.

Orbiter Structural Design

NASA faced several challenges in the structural design of the Orbiter. These challenges were greater than those of any previous aircraft, launch vehicle, or spacecraft, and the Orbiter was all three. Yet, the space agency proceeded with tenacity and confidence, and ultimately reached its goals. In fact, 30 years of successful shuttle flights validated the agency's unique and innovative approaches, processes, and decisions regarding characteristics of design.

A few of the more significant challenges NASA faced in Orbiter structural design included the evolution of design loads. The Orbiter structure was designed to an early set of loads and conditions and certified to a later set. The shuttle achieved first-flight readiness through a series of localized structural modifications and operational flight constraints. During the early design phase, computer analyses using complex calculations like finite-element models and techniques for combined thermal and mechanical loads were not possible. Later advances in analytical methods, coupled with test data, allowed significant reductions in both scope and cost of Orbiter structural certification. The space agency had to face other challenges. Structural efficiency had to be compromised to assure versatile payload attachment and payload bay door operations. Skin buckling had to be avoided to assure compatibility with the low-strength Thermal Protection System tiles. Composite materials

beyond the state of the art were needed. The crew compartment had to be placed into the airframe such that the pressurized volume would effectively "float." And it was impractical to test the full airframe under combined mechanical and thermal loads.

Thousands of analytical design loads and conditions were proven acceptable with flight data with one exception:

the ascent wing loads were greater than predicted because of the effect the rocket exhaust plume had on the aerodynamic pressure distribution. As a result, early flights were flown within limited flight regimes to assure that the structural capability of the wings was not exceeded. The wings were later "strengthened" with minor changes in the design and weight.

Shuttle Wing Loads—Testing and Modification Led to Greater Capacity

Orbiter wing loads demonstrated the importance of anchoring the prediction or grounding the analysis with flight data in assuring a successful flight. The right wing of Columbia was instrumented with strain gauges for the test flights and was load-calibrated to verify the in-flight air load distribution. The wing was also instrumented with pressure gauges; however, the number was limited due to on-board recorder space limitations. This resulted in the need to obtain additional pressure data.

Space Transportation System (STS)-1 (1981) data indicated higher shear in the aft spar web than was predicted. NASA conducted analyses to determine the location and magnitude of forces causing this condition. The results indicated an additional load along the outboard wing leading edge (elevon hinge line). Data obtained on STS-2 (1981) through STS-4 (1982) substantiated these results. This caused concern for the operational wing limits that were to be imposed after the flight test period.

The additional load caused higher bending and torsion on the wing structure, exceeding design limits. The flight limits, in terms of angle of attack and sideslip, would have to be restricted with an attendant reduction in performance.

The recovery plan resulted in modification to the wing leading edge fittings. The major impact was to the structure between the upper and lower wing skins, which were graphite-epoxy. These required angle stiffeners on each flat to increase the buckling stress. The weight of the modifications resulted in a loss of performance. The resulting flight envelope was slightly larger than the original when accounting for the negative angle-of-attack region of the flight regime.

Payload Access and Structural Attachments—Mid-Fuselage and Payload Bay Doors

NASA designed the mid-fuselage of the Orbiter to be "flexible" so as to accommodate the closing of payload bay doors in space. The design also had to accommodate a wide range of payload sizes, weights, and number.

The payload bay doors were an integral part of the fuselage structure. The classical structural design would have the doors provide strength when the fuselage encountered loads from bending, twisting, shear, internal pressure, and thermal gradients. The doors also had to open in space to provide access to the payload and enable the radiators to radiate heat to space. Equally important, the doors had to close prior to re-entry into Earth's atmosphere to provide aerodynamic shape and thermal protection.

To balance the functional and strength requirements, engineers designed the doors to be flexible. The flexibility and zipper-like closing ensured that the doors would close in orbit even if distorted thermally or by changes in the gravity environment (from Earth gravity to microgravity). If the latches did not fully engage, the doors could not be relied on to provide strength during re-entry for fuselage bending, torsion, and aerodynamic pressure. Thus, the classical design approach for ascent was not possible for re-entry. The bulkheads at each end of the payload section and the longerons on each side required additional strength. To reduce weight and thermal distortion, engineers designed the doors using graphite epoxy. This was the largest composite structure on any aircraft or spacecraft at the time.

Typical Payload Attachment Scheme
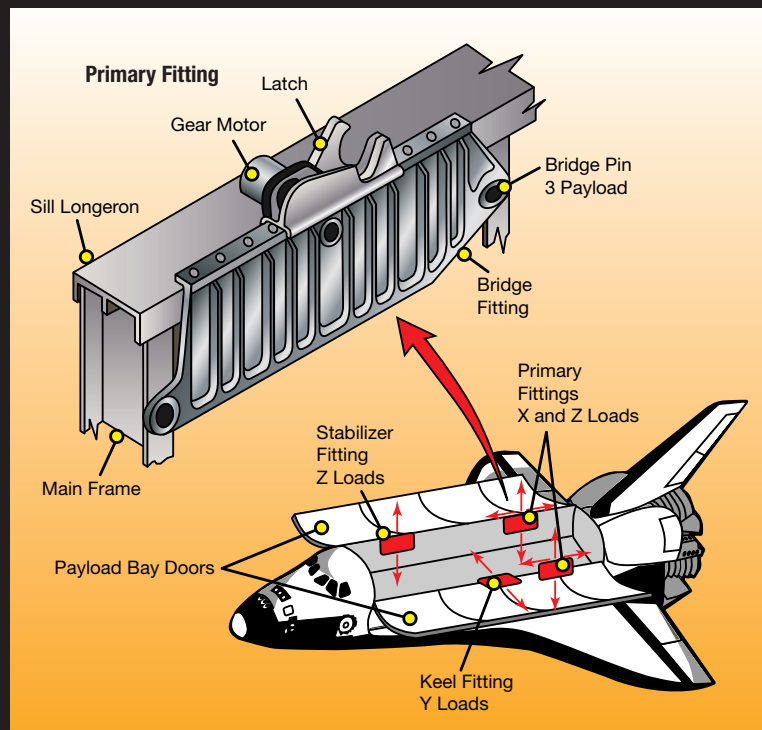
Sets of moveable attachment fittings on the longerons and frames accommodated multiple payloads. The Monte Carlo analyses of the full spectrum of payload quantities, sizes, mass properties, and locations determined the mid-fuselage design loads. These design loads were enveloped based on a combination of 10 million load cases. Decoupling the design of the mid-fuselage and payloads enabled a timely design of both.

The mid-fuselage had to accommodate the quantity, size, weight, location, stiffness, and limitations of known and unknown payloads. An innovative design approach needed to provide a statically determinant attachment system between the payloads and mid-fuselage. This would decouple the bending, twisting, and shear loads between the two structures, thus enabling engineers to design both without knowing the stiffness characteristic of each.

Designing to Minimize Local Deflections

The Orbiter skin was covered with more than 30,000 silica tiles to withstand the heat of re-entry. These tiles had a limited capacity to accommodate structural deflections from thermal gradients. The European supersonic Concorde passenger aircraft (first flown in 1969 and in service from 1976 to 2003) and the SR-71 US military

aircraft encountered significant thermal gradients during flight. The design approach in each was to reduce stresses induced by the thermal gradients by enabling expansion of selected regions of the structure; e.g., corrugated wing skins for the SR-71 and "slots" in the Concorde fuselage. After consulting with the designers of both aircraft, NASA concluded that the Orbiter design should account for thermally induced stresses but resist large expansions and associated skin buckling. This brute-force approach protected the attached silica tile as well as simplified the design and manufacture of the Orbiter airframe.

NASA developed these design criteria so that if the thermal stresses reduced the mechanical stresses, the reductions would not be considered in the combined stress calculations.

To determine the thermally induced stresses, NASA established deterministic temperatures for eight initial temperature conditions on the Orbiter at the time of re-entry as well as at several times during re-entry. Engineers generated 120 thermal math models for specific regions of the Orbiter. Temperatures were extrapolated and interpolated to nodes within these thermal math models.
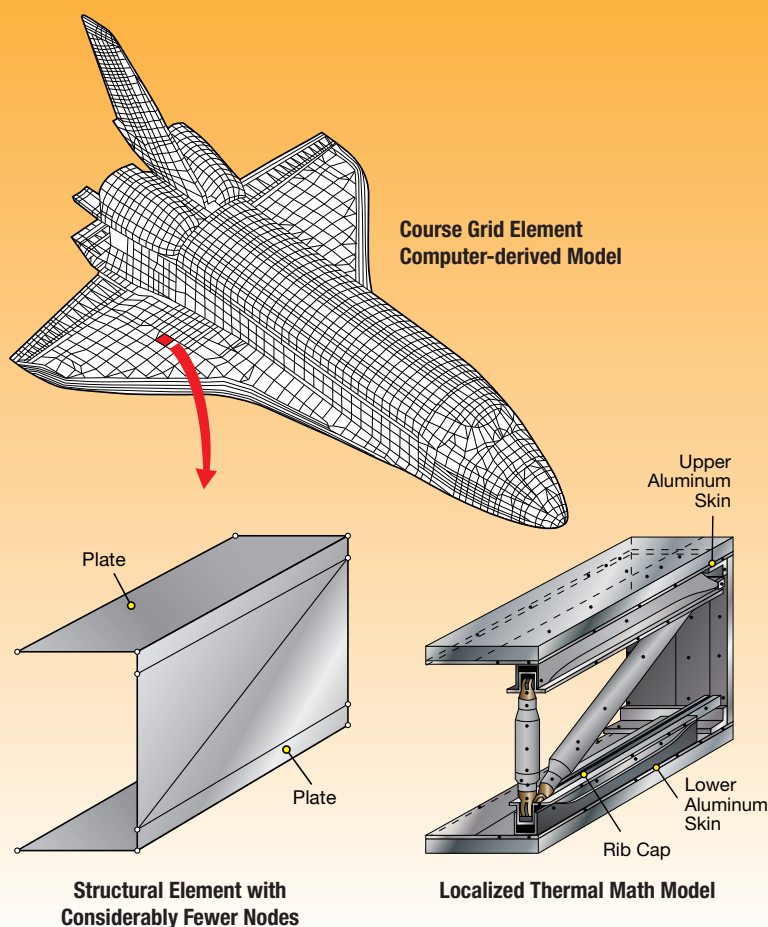
Use of Unique Advanced Materials

Even though the Orbiter was a unique aircraft and spacecraft, NASA selected a conventional aircraft skin/stringer/frame design approach. The space agency also used conventional aircraft material (i.e., aluminum) for the primary structure, with exceptions in selected regions where the use of advanced state-of-the-art composites increased efficiency due to their lower density, minimum thermal expansion, or higher modulus of elasticity.

Other exceptions to the highly reliable conventional structures were the graphite-epoxy Orbital Maneuvering System skins, which were part of a honeycomb sandwich structure. These graphite honeycomb structures had a vented core to relieve pressure differentials across the face sheets during flight. They also required a humidity-controlled environment while on the ground to prevent moisture buildup in the core. Such a buildup could become a source of steam during the higher temperature regimes of flight. Finally, during the weight-savings program instituted on Discovery, Atlantis, and Endeavour, engineers replaced the aluminum spar webs in the wing with a graphite/epoxy laminate.

Large doors, located on the bottom of the Orbiter, were made out of beryllium. These doors closed over the External Tank umbilical cavity once the vehicle
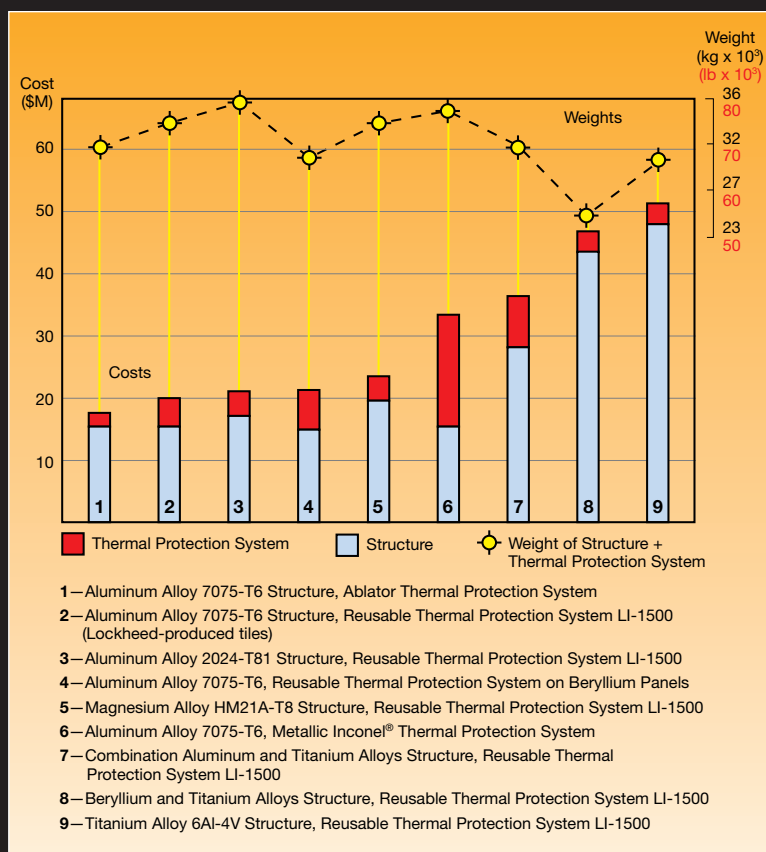

Orbiter Thermal Stress Analysis Modeling

Course Grid Element Computer-derived Model

Plate

Plate

Structural Element with Considerably Fewer Nodes

Upper Aluminum Skin

Lower Aluminum Skin

Rib Cap

Localized Thermal Math Model

Early Trade Studies Showed Cost Benefits That Guided Materials Selection

Titanium offered advantages for the primary structure because of higher temperature capability—315°C vs. 177°C (600°F vs. 350°F). When engineers considered the combined mass of the structure and Thermal Protection System, however, they noted a less than 10% difference. The titanium design cost was 2.5 times greater. The schedule risk was also greater. NASA considered other combinations of materials for the primary structure and Thermal Protection System and conducted a unit cost comparison. This study helped guide the final selections and areas for future development.

Orbiter Structure/Thermal Protection System First Unit Cost Comparison

Legend:
- ■ Thermal Protection System
- ■ Structure
- ○ Weight of Structure + Thermal Protection System

1—Aluminum Alloy 7075-T6 Structure, Ablator Thermal Protection System
2—Aluminum Alloy 7075-T6 Structure, Reusable Thermal Protection System LI-1500 (Lockheed-produced tiles)
3—Aluminum Alloy 2024-T81 Structure, Reusable Thermal Protection System LI-1500
4—Aluminum Alloy 7075-T6, Reusable Thermal Protection System on Beryllium Panels
5—Magnesium Alloy HM21A-T8 Structure, Reusable Thermal Protection System LI-1500
6—Aluminum Alloy 7075-T6, Metallic Inconel® Thermal Protection System
7—Combination Aluminum and Titanium Alloys Structure, Reusable Thermal Protection System LI-1500
8—Beryllium and Titanium Alloys Structure, Reusable Thermal Protection System LI-1500
9—Titanium Alloy 6Al-4V Structure, Reusable Thermal Protection System LI-1500
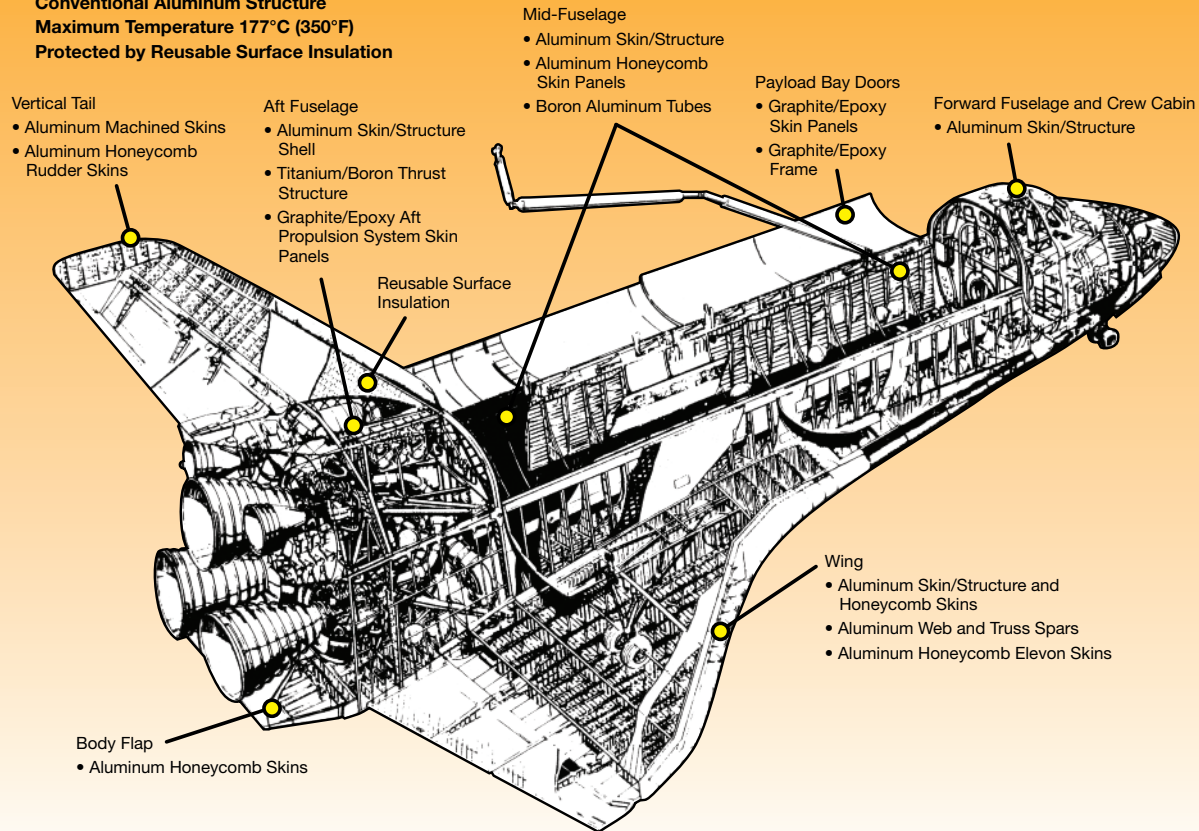
environment generated by ascent heating. The beryllium material allowed the doors to be relatively lightweight and very stiff, and to perform well at elevated temperatures. The superior thermal performance allowed the door, which measured 25.4 mm (1 in.) in thickness, to fly without internal insulation during launch. Since beryllium can be extremely toxic, special procedures applied to those working in its vicinity.

The truss structure that supported the three Space Shuttle Main Engines was stiff and capable of reacting to over a million pounds of thrust. The 28 members that made up the thrust structure were machined from diffusion-bonded titanium. Titanium strips were placed in an inert environment and bonded together under heat, pressure, and time. This fused the titanium strips into a single, hollow, homogeneous mass. To increase the stiffness, engineers bonded layers of boron/epoxy to the outer surface of the titanium beams. The titanium construction was reinforced in select areas with boron/epoxy tubular struts to minimize weight and add stiffness. Overall, the integrated metallic composite construction reduced the thrust structure weight by 21%, or approximately 409 kg (900 pounds).

NASA used approximately 168 boron aluminum tubes in the mid-fuselage frames as stabilizing elements. Technicians bonded these composite tubes to titanium end fittings and saved approximately 139 kg (305 pounds) over a conventional aluminum tube design. During ground operations, however, composite tubes in high traffic areas were repeatedly damaged and were eventually replaced with an aluminum design to increase robustness during vehicle turnaround.

was on orbit. These approximately 1.3-m (50-in.) square doors maintained the out-of-plane deflection to less than 20 mm (0.8 in.) to avoid contact with adjacent tiles. They also had the ability to withstand a 260°C (500°F)

Orbiter Structure—Structural Arrangement and Location of Composite Materials

Conventional Aluminum Structure
Maximum Temperature 177°C (350°F)
Protected by Reusable Surface Insulation

Vertical Tail
• Aluminum Machined Skins
• Aluminum Honeycomb Rudder Skins

Aft Fuselage
• Aluminum Skin/Structure Shell
• Titanium/Boron Thrust Structure
• Graphite/Epoxy Aft Propulsion System Skin Panels

Reusable Surface Insulation

Mid-Fuselage
• Aluminum Skin/Structure
• Aluminum Honeycomb Skin Panels
• Boron Aluminum Tubes

Payload Bay Doors
• Graphite/Epoxy Skin Panels
• Graphite/Epoxy Frame

Forward Fuselage and Crew Cabin
• Aluminum Skin/Structure

Wing
• Aluminum Skin/Structure and Honeycomb Skins
• Aluminum Web and Truss Spars
• Aluminum Honeycomb Elevon Skins

Body Flap
• Aluminum Honeycomb Skins

After the initial design of Challenger and Columbia, NASA initiated a weight-savings program for the follow-on vehicles—Discovery, Atlantis, and Endeavour. The space agency achieved weight savings through optimization of aluminum structures and replaced the aluminum spar webs in the wing with a graphite/epoxy laminate.

"Floating" Crew Compartment

The crew compartment structure "floated" inside the forward fuselage. The crew compartment was attached to the forward fuselage at four discrete points, thus enabling a simpler design (for pressure and inertia loads only) and greater thermal isolation. The crew compartment was essentially a pressure vessel and the only pressurized compartment in the Orbiter. To help assure pressure integrity, the aluminum design withstood a large noncritical crack while maintaining cabin pressure. The "floating" crew compartment reduced weight over an integrated forward fuselage design and simplified manufacturing.
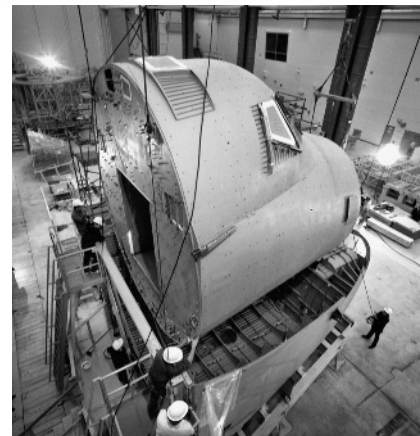
The crew cabin being installed in the forward fuselage.

Innovative Concept for Jackscrews Prevented Catastrophic Failures

Follower Nut   Primary Nut

More than 4,000 jackscrews were in use around Kennedy Space Center (KSC) during the Space Shuttle era. NASA used some of these jackscrews on critical hardware. Thus, a fail-safe, continue-to-operate design was needed to mitigate the possibility of a catastrophic event in case of failure.

A conventional jackscrew contained only one nut made of a material softer than that of the threaded shaft. With prolonged use, the threads in the nut would wear away. If not inspected and replaced after excessive wear, the nut eventually failed. KSC's fail-safe concept for machine jackscrews incorporated a redundant follower nut that would begin to bear the axial jack load on the failure of the primary nut.

Unlike the case of a conventional jackscrew, it was not necessary to relieve the load to measure axial play or disassemble the nut from the threaded shaft to inspect the nut for wear. Instead, wear could be determined by measuring the axial gap between the primary nut and the follower nut.

Additionally, electronic and mechanical wear indicators were used to monitor the gap during operation or assist during inspection. These devices would be designed to generate a warning when the thread was worn to a predetermined thickness. The fail-safe, continue-to-operate design concept offered an alternative for preventing catastrophic failures in jackscrews, which were used widely in aeronautical, aerospace, and industrial applications.

Orbiter Structure Qualification

The conventional strength and life certification approach for a commercial or military aircraft is to demonstrate the ultimate strength and fatigue (life) capacities with a dedicated airframe for each. Similarly, NASA planned two full-scale test articles at the outset of the Orbiter design, development, test, and evaluation program. Ultimately, the Orbiter structure was certified with an airframe that became a flight vehicle and a series of smaller component test articles that comprised about 30% of the flight hardware. The space agency did not take additional risks, and the program costs for ground tests were reduced by several hundred million dollars.

Ultimate Strength Integrity

Virtually all of the Orbiter's primary structure had significant thermal stress components. Therefore, thermal stress had to be accounted for when certifying the design for ultimate strength. Yet, it was impractical—if not impossible—to simulate the correct combination of temperatures and mechanical loads for the numerous conditions associated with ascent, spaceflight, and re-entry into Earth's atmosphere, especially for transient cases of interest. NASA reached this conclusion after consulting with the Concorde aircraft structural experts who conducted multiyear, expensive combined environment tests.

Orbiter strength integrity would be certified in a bold and unconventional approach that used the Challenger (Orbiter) as the structural test article. Rather than testing the ultimate load (140% of maximum expected loads), NASA would test to 120% of limit

mechanical load, use the test data to verify the analytical stress models, and analytically prove that the structure could withstand 140% of the combined mechanical and thermal stresses.

The structural test article was mounted in a horizontal position at the External Tank reaction points and subjected to a ground test program at the Lockheed test facility in Palmdale, California. The 390,900-kg (430-ton) test rig contained 256 hydraulic jacks that distributed loads across 836 application points to simulate various stress levels. Initial influence coefficient tests involved the application of approximately 150 load conditions as point loads on the vehicle. These unit load cases exercised the structure at the main engine gimbal and actuator attachments, payload fittings, and interfaces on the wing, tail, body flap, and Orbital Maneuvering System pods. Engineers measured load vs. strain at numerous locations and then used those measurements for math model correlation. They also used deflection measurements to substantiate analytical stiffness matrices.

The Orbiter airframe was subjected to a series of static test conditions carried to limit plus load levels (approximately 120% of limit). These conditions consisted of a matrix of 30 test cases representative of critical phases (boost, re-entry, terminal area energy management, and landing) to simulate design mechanical loads plus six thrust vector-only conditions. These tests verified analytically predicted internal load distributions. In conjunction with analysis, the tests also confirmed the structural integrity of the Orbiter airframe for critical design limit loads. Engineers used these data to support evaluation of the ultimate factor of safety by analysis. Finally, they used the test series to evaluate strains from the developmental flight instrumentation.

Space Shuttle Pogo—NASA Eliminates "Bad Vibrations"

Launch vehicles powered by liquid-fueled, pump-fed rocket engines frequently experience a dynamic instability that caused structural vibrations along the vehicle's longitudinal axis. These vibrations are referred to as "Pogo."
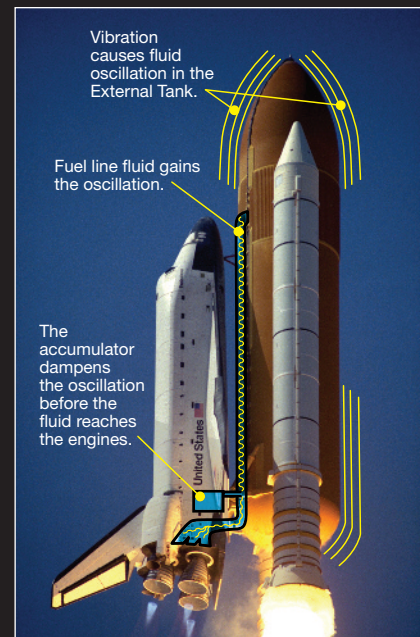
As Astronaut Michael Collins stated, "The first stage of Titan II vibrated longitudinally so that someone riding on it would be bounced up and down as if on a pogo stick."

In technical terms, Pogo is a coupled structure/propulsion system instability caused by oscillations in the propellant flow rate that feeds the engines. The propellant flow rate oscillations can result in oscillations in engine thrust. If a frequency band of the thrust oscillations is in phase with the natural frequency of engine structure and is of sufficient magnitude to overcome structural damping, the amplitude of the propellant flow rate oscillation will increase. Subsequently, this event will increase the amplitude of the thrust oscillation. This sequence can lead to Pogo instability, with the possible result in an unprogrammed engine shutdown and/or structural failure—both of which would result in loss of mission.

Most NASA launch vehicles experienced Pogo problems. Unfortunately, the problem manifested itself in flight and resulted in additional testing and analytical work late in the development program. The solution was to put an accumulator in the propellant feedline to reduce propellant oscillations.

The Space Shuttle Program took a proactive approach with a "Pogo Prevention Plan" drafted in the early 1970s. The plan called for comprehensive stability analysis and testing programs. Testing consisted of modal tests to verify the structural dynamic characteristics, hydroelastic tests of External Tank and propellant lines, and pulse testing of the Space Shuttle Main Engines. The plan baselined a Pogo suppression system—the first NASA launch vehicle to have such

Vibration causes fluid oscillation in the External Tank.

Fuel line fluid gains the oscillation.

The accumulator dampens the oscillation before the fluid reaches the engines.

a feature. The space agency selected and included an accumulator in the design of the main engines. This approach proved successful. Flight data demonstrated that the Space Shuttle was free of Pogo.
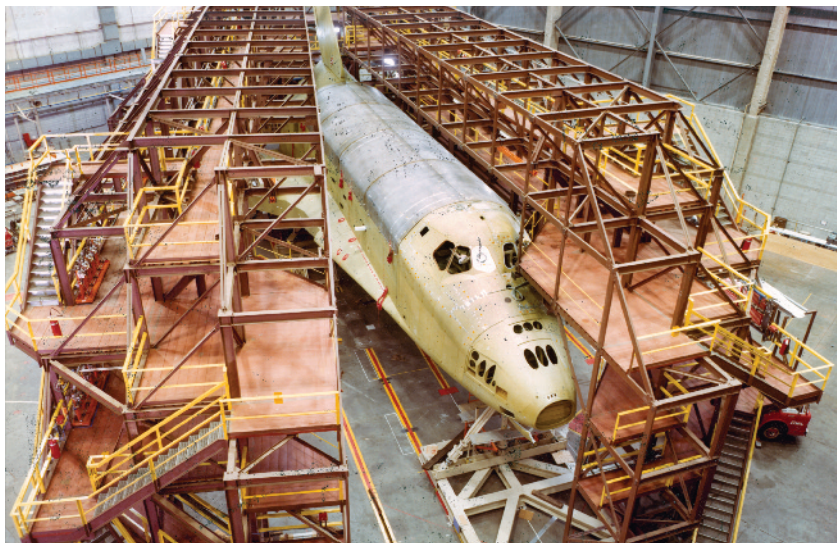
Test rig surrounds the Orbiter structural test article, Challenger, at the Lockheed Test Facility in Palmdale, California.

After the limit plus tests, the forward fuselage of the structural test article was subjected to a thermal environment gradient test. This testing entailed selective heating of the external skin regions with 25 zones. Gaseous nitrogen provided cooling. NASA used the data to assess the effects of thermal gradients and assist in the certification of thermal stresses by analysis techniques. Finally, the aft fuselage of the structural test article was subjected to internal/external pressures to provide strain and deflection data to verify the structural adequacy of the aft bulkhead and engine heat shield structures.

The structural test article subjected the Orbiter airframe to approximately 120% of limit load. To address ultimate load (140%) in critical areas, NASA conducted a series of supplemental tests on two major interfaces and 34 component specimens. The agency chose these specimens based on criticality of failure, uncertainty in analysis, and minimum fatigue margin. Designated specimens were subjected

to fatigue testing and analysis to verify the 100-mission life requirement. Finally, NASA tested all components to ultimate load and gathered data to compare predictions.

This unprecedented approach was challenged by NASA Headquarters and reviewed by an outside committee of experts from the "wide body" commercial aircraft industry. The experts concurred with the approach.

Acoustic Fatigue Integrity

Commercial and military aircraft commonly have a design life of 20,000 hours of flight composed of thousands of take offs and landings. As a result, the fatigue life is a design factor. The Orbiter, on the other hand, had a design life of 100 missions and a few hundred hours of flight in the atmosphere, but the acoustic environment during ascent was very high. Certification of acoustic fatigue life had to be accomplished.

The challenge was to certify this large, complex structure for a substantial number of combined acoustic, mechanical, and thermal conditions. No existing test facilities could accommodate a test article the size of the Orbiter or simulate all of the loads and environments.

The acoustic fatigue certification program was as innovative as that of the ultimate strength certification. The approach was to test a representative structure of various forms, materials, and types of construction in representative acoustic environments until the structure failed. This

Orbiter Acoustic Fatigue Test Articles

These acoustic fatigue test articles (shaded in blue) are representative of structure and environment.

Forward Fuselage (under body)

Wing Shadow (internal)

Wing Carry Through Rib (internal)
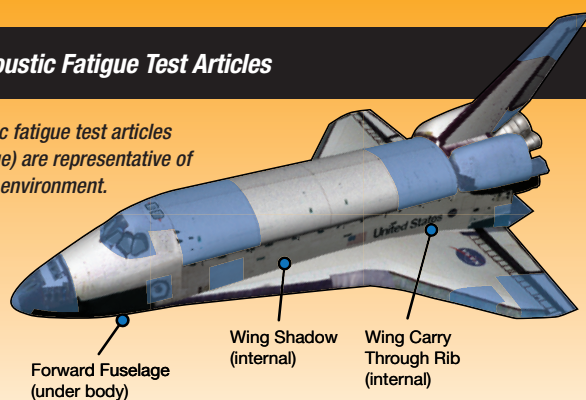
Nozzle Flexible Bearing—Steering the Reusable Solid Rocket Motor

At Space Shuttle liftoff, initial steering was controlled in large part by the reusable solid rocket motors' movable nozzles. Large hydraulic actuators were attached to each nozzle. On command, these actuators mechanically vectored the nozzle, thereby redirecting the supersonic flow of hot gases from the motor.

A flexible bearing allowed the nozzle to be vectored. At about 2.5 m (8 ft) in diameter and 3,200 kg (7,000 pounds), this bearing was the largest flexible bearing in existence. The component had to vector up to 8 degrees while maintaining a pressure-tight seal against the combustive gases within the rocket, withstand high loads imparted at splashdown, and fit within the constraints of the solid rocket motor case segments. It also had to be reusable up to nine times.

The structure consisted of alternating layers of natural rubber (for flexibility) and steel shims (for strength and stiffness). The layers were spherically shaped,
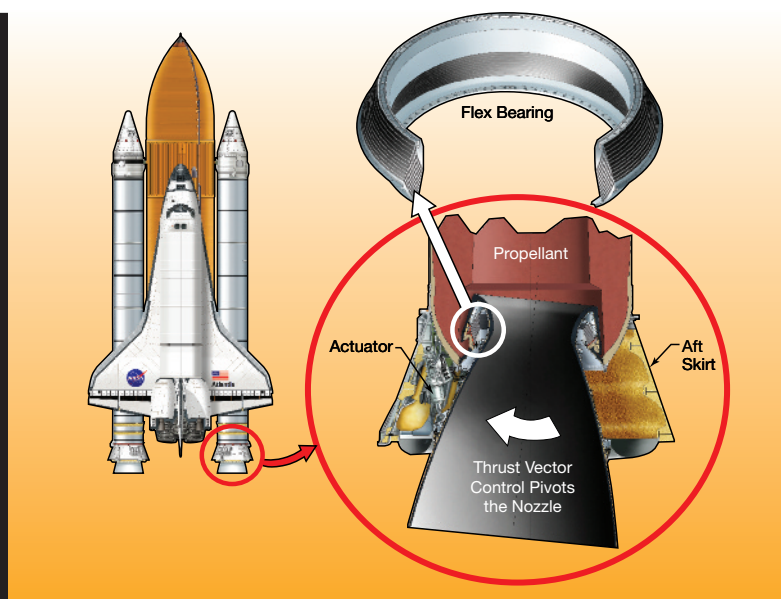
During the first minutes of flight, a Thrust Vector Control System housed at the base of each solid rocket motor provided a majority of the steering capability for the shuttle. A flexible bearing enabled nozzle movement. Two hydraulic actuators generated the mechanical force needed to move the nozzle.

allowing the nozzle to pivot in any direction. Forces from the actuators induced a torque load on the bearing that strained the rubber layers in shear, with each layer rotating a proportional part of the total vector angle. This resulted in a change in nozzle angular direction relative to the rocket motor centerline.

The most significant manufacturing challenge was producing a vulcanization bond between the rubber and the shims.

Fabrication involved laying up the natural rubber by hand between the spherically shaped shims. Vulcanization was accomplished by applying pressure while controlling an elevated temperature gradient through the flexible bearing core. This process cured the rubber and vulcanized it to the shims in one step. The completed bearing underwent rigorous stretching and vectoring tests, including testing after each flight, as part of the refurbishment process.

established the level of damage that would be allowed for each type of structure. NASA selected 14 areas of the Orbiter to represent the various structural configurations.

The allowable damage was reduced analytically to account for the damage induced by the flight loads and temperature cycles for all regions of the vehicle.

Because of the high fatigue durability of the graphite-epoxy construction of the payload bay doors and Orbital Maneuvering System pods, these structures were not tested to failure. Instead, the strains measured during the acoustic tests were correlated with mathematical models and adequate fatigue life was demonstrated analytically. These test articles were subsequently used as flight hardware.

Summary

The unique approaches taken during the Space Shuttle Program in validating the structural integrity of the Orbiter airframe set a precedent in the NASA programs that followed. Even as more accurate analysis software and faster computers are developed, the need for anchoring predictions in the reality of testing remains a cornerstone in the safe flight of all space vehicles.

Pressure Vessel Experience

In the 1970s, NASA made an important decision—one based on previous experience and emerging technology—that would result in significant weight savings for shuttle. The agency implemented the Composite Overwrapped Pressure Vessels Program over the use of all-metal designs for storing high-pressure gases, 2,068 – 3,361 N/cm² (3,000 – 4,875 psi) oxygen, nitrogen, and helium. The agency used 22 such vessels in the Environmental Control and Life Support System, Reaction Control System, Main Propulsion System, and Orbital Maneuvering System. The basic new design consisted of a gas or liquid impermeable, thin-walled metal liner wrapped with a composite overwrap for primary pressure containment strength.

Safety—Always a Factor

The Space Shuttle Program built on the lessons learned from the Apollo Program. The pressure vessels were constructed of titanium and designed such that the burst pressure was only 1.5 times the operating pressure (safety factor). This safety factor was unprecedented at the time. To assure the safety of tanks with such a low margin of safety, NASA developed a robust qualification and acceptance program. The technical knowledge gained during the Apollo Program was leveraged by the shuttle, with the added introduction of a new type of pressure vessel to further reduce mass.

The Brunswick Corporation, Lake Forest, Illinois, developed, for the shuttle, a composite overwrapped pressure vessel for high-pressure oxygen, nitrogen, and helium storage. The metallic liners were made of titanium (Inconel® for the oxygen systems) overwrapped with DuPont™ Kevlar® in an epoxy matrix. Switching from solid titanium tanks to composite overwrapped pressure vessels reduced the Space Shuttle tank mass by approximately 209 kg (460 pounds).
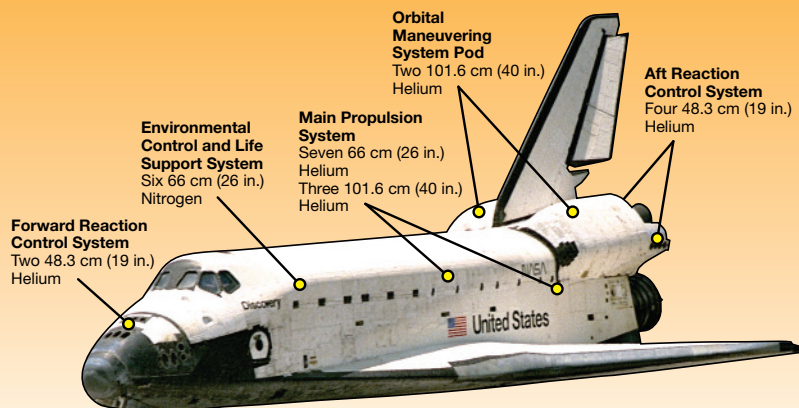
Since the shuttle was reusable and composite overwrapped pressure vessels were a new technology, the baseline factor of safety was 2.0. As development progressed, NASA introduced and instituted a formal fracture control plan based on lessons learned in the Apollo Program. As the composite overwrapped pressure vessels were fracture-critical items—e.g., their failure would lead to loss of vehicle and crew—fracture control required extensive lifetime testing of the vessels to quantify all failure modes. The failure mechanisms of the composite were just beginning to be understood. Kevlar® is very durable, so minor damage to the overwrap was not critical. NASA, however, discovered that the composite could fail when under a sustained stress, less than its ultimate capability, and could fail without indication. This failure mode of the composite was called "stress rupture" and could lead to a catastrophic burst of the pressure vessel since the metallic liner could not carry the pressure stress alone.

In the late 1970s, engineers observed unexpectedly poor stress rupture performance in the testing of Kevlar® strands at the Lawrence Livermore Nationale Laboratory in Livermore, California. As a result, NASA contracted with that laboratory to study the failure modes of the Kevlar® fiber for application in the shuttle tanks. Technicians conducted hundreds of tests on individual Kevlar® fibers, fiber/epoxy strands, and subscale vessels.

The development program to characterize all the failure modes of the composite overwrapped pressure vessels set the standard for all spaceflight programs. Therefore, as tank development proceeded, NASA used the fracture control test program to

Composite Overwrapped Pressure Vessels

Orbital Maneuvering System Pod
Two 101.6 cm (40 in.) Helium

Aft Reaction Control System
Four 48.3 cm (19 in.) Helium

Environmental Control and Life Support System
Six 66 cm (26 in.) Nitrogen

Main Propulsion System
Seven 66 cm (26 in.) Helium
Three 101.6 cm (40 in.) Helium

Forward Reaction Control System
Two 48.3 cm (19 in.) Helium

NASA Puts Vessels to the "Stress Test"

In 1978, NASA developed and implemented a "fleet leader" test program to provide Orbiter subscale vessel stress rupture data for comparison to existing strand and subscale vessel data. Vessels in the test program were subscale in size and used aluminum liners instead of titanium, yet they were built by the same company manufacturing the Orbiter composite overwrapped pressure vessels using the same materials, equipment, and processes/procedures. These vessels were put to test at Johnson Space Center in Houston, Texas.

The test program consisted of two groups of vessels—15 vessels tested at ambient temperature conditions and an approximate stress level of 50% of ultimate strength; and 10 vessels tested at approximately 50% of average strength and an elevated temperature in an attempt to accelerate stress rupture failure. For the elevated temperature testing, 79°C (175°F) was

chosen as the test temperature for both groups. Engineers performed periodic depressurizations/repressurizations to simulate Orbiter usage and any potential effects.

The ambient temperature vessels were pressurized for nearly 25 years without failure before NASA stopped testing. The flight vessels only accumulated a week or two worth of pressure per

mission, so the ground tests led the fleet by a significant margin.

For the accelerated 79°C (175°F) temperature testing, the first failure occurred after approximately 12 years and the second at 15 years of pressure. These stress rupture failures indicated that the original stress rupture life predictions for composite overwrapped pressure vessels were conservative.

justify a safe reduction in the factor of safety on burst from 2.0 to 1.5, resulting in an additional 546 kg (1,203 pounds) of mass saved from the Orbiter.

Even with all of the development testing, two non-stress rupture composite overwrapped pressure vessels failures occurred on shuttle. The complexity of the welding process on certain materials contributed to these failures. To build a spherical

pressure vessel, two titanium hemispheres had to be welded together to form the liner. Welding titanium is difficult and unintentional voids are sometimes created. Voids in the welds of two Main Propulsion System vessels had been missed during the acceptance inspection. In May 1991, a Main Propulsion System helium pressurization vessel started leaking on the Atlantis prior to the launch of

Space Transportation System (STS)-43. NASA removed these vessels from the Orbiter.

The subsequent failure investigation found that, during manufacture, 89 pores formed in the weld whereas the typical number for other Orbiter vessels was 15. Radiographic inspection of the welds showed that the pores had initiated fatigue cracks that eventually broke through the liner, thereby causing

the leak. While this inspection was ongoing, the other Main Propulsion System vessel on Atlantis started leaking helium—once again due to weld porosity. NASA reviewed all other vessels in service, but none had weld porosity levels comparable to the two vessels that had leaked.

Space Shuttle Experiences Influence Future Endeavors

NASA's Orbiter Project pushed the technology envelope for pressure vessel design. Lessons learned from development, qualification, and in-service failures prompted the International Space Station (ISS) and future space and science missions to develop more robust requirements and verification programs. The ISS Program instituted structure controls based on the shuttle investigation of pressure vessels. No other leaks in pressure vessel tanks occurred through 2010—STS-132. For instance, the factor of safety on burst pressure was 1.5; damage tolerance of the composite and metallic liner was clearly addressed through qualification testing and operational damage control plans; radiographic inspection of liner welds was mandatory with acceptable levels of porosity defined; and material controls were in place to mitigate failure from corrosion, propellant spills, and stress rupture. These industry standard design requirements for composite overwrapped pressure vessels are directly attributable to the shuttle experience as well as its positive influence on future spaceflight.

Fracture Control Technology Innovations— From the Space Shuttle Program to Worldwide Use

A fundamental assumption in structural engineering is that all components have small flaws or crack-like defects that are introduced during manufacturing or service. Growth of such cracks during service can lead to reduced service life and even catastrophic structural failure. Fracture control methodology and fracture mechanics tools are important means for preventing or mitigating the adverse effects of such cracks. This is important for industries where structural integrity is of paramount importance.
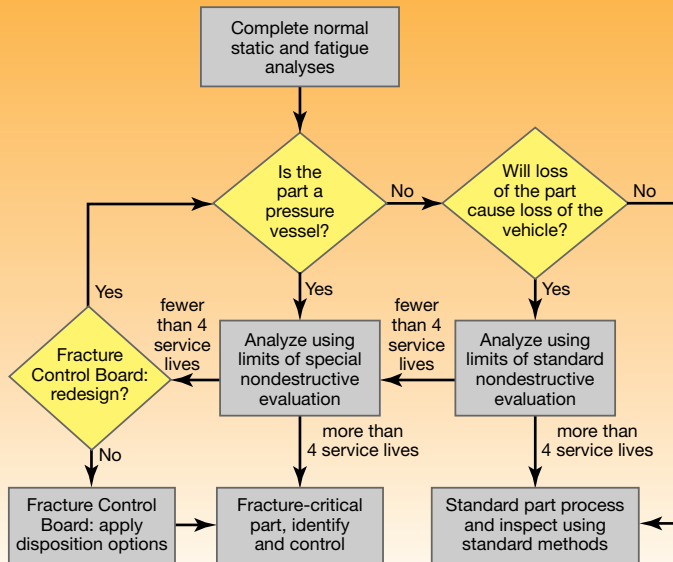
Prior to the Space Shuttle, NASA did not develop or implement many fracture mechanics and fracture control applications during the design and build phases of space vehicles. The prevailing design philosophy at the time was that safety factors on static strength provided a margin against fracture and that simple proof tests of tanks (pressure vessels) were sufficient to demonstrate the margin of safety. In practice, however, the Apollo Program experienced a number of premature test failures of pressure vessels that resulted in NASA implementing a version of fracture control referred to as "proof test logic." It was not until the early 1960s that proof tests were sufficiently understood from a fracture mechanics point of view—that proof tests could actually be used, in some cases, to ensure the absence of initial flaws of a size that could cause failure within a pressure vessel's operating conditions.

The application of proof test logic required the determination of environmental crack growth thresholds for all environments to which the pressure vessels were exposed while pressurized as well as development of fracture toughness values and cyclic crack growth rates for materials used in the pressure vessels. The thresholds resulted in pressurization restrictions and environmental control of all Apollo pressure vessels. In effect, proof test logic formed the first implementation of a rigorous fracture control program in NASA.

Fracture Control Comes of Age

The legacy of the Apollo pressure vessel failure experience was that NASA, through the Space Shuttle Program, became an industry leader in the development and application of fracture mechanics technology and fracture control methodology. Although proof test logic worked successfully for the Apollo pressure vessels, the Space Shuttle Program brought with it a wide variety of safety-critical, structurally complex components (not just pressure vessels), materials with a wide range of fracture properties, and an aircraft-like fatigue environment— all conditions for which proof test logic methodology could not be used for flaw screening purposes. The shuttle's reusable structure demanded a more comprehensive fracture control methodology. In 1973, the Orbiter Project released its fracture control plan that set the requirements for and helped guide the Orbiter hardware through the design and build phases of the project.

Complete normal static and fatigue analyses

↓

Is the part a pressure vessel?

— No → **Will loss of the part cause loss of the vehicle?**

Is the part a pressure vessel? — Yes (left) → **Fracture Control Board: redesign?**

Fracture Control Board: redesign? — Yes / fewer than 4 service lives → **Analyze using limits of special nondestructive evaluation**

Is the part a pressure vessel? — Yes (down) → **Analyze using limits of special nondestructive evaluation**

Will loss of the part cause loss of the vehicle? — No → (right path)

Will loss of the part cause loss of the vehicle? — Yes / fewer than 4 service lives → **Analyze using limits of standard nondestructive evaluation**

Fracture Control Board: redesign? — No → **Fracture Control Board: apply disposition options**

Analyze using limits of special nondestructive evaluation — more than 4 service lives → **Fracture-critical part, identify and control**

Fracture Control Board: apply disposition options → **Fracture-critical part, identify and control**

Analyze using limits of standard nondestructive evaluation — more than 4 service lives → **Standard part process and inspect using standard methods**

Early Shuttle Fracture Control

Fracture control, as practiced early in the Space Shuttle Program, was a three-step process: select the candidate fracture critical components, perform fracture mechanics analyses of the candidates, and disposition the components that had insufficient life.

Design and stress engineers selected the candidate fracture critical components. The selection was based on whether failure of the component from crack propagation could lead to a loss of life or vehicle. Certain components, such as pressure vessels, were automatically considered fracture critical. Performing a fracture mechanics analysis of the candidates started with an assumed initial crack located in the most unfavorable location in the component. The size of the assumed crack was typically based on the nondestructive inspection that was performed on the component. The fracture mechanics analysis

required knowledge of the applied stress, load spectrum, environment, assumed initial crack size, materials fracture toughness, and materials fatigue and environmental crack growth properties. Fracture analysis was required to show a service life of four times the shuttle's 100-mission design life.

There were a number of options for dispositioning components that had insufficient life. These options included the following:

■ Redesigning the component when weight and cost permitted

■ Conducting nondestructive inspection with a more sensitive technique where special nondestructive evaluation procedures allowed a smaller assumed crack size

■ Limiting the life of the component

■ Considering multiple element load paths

■ Demonstrating life by fracture mechanics testing of the component

■ Refining the loading based on actual measurements from the full-scale structural test articles

In addition to being a fundamental part of the structural design process, fracture mechanics became a useful tool in failure analysis throughout the Space Shuttle Program.

Fracture Control Evolves with Payloads

The shuttle payload community further refined the Orbiter fracture control requirements to ensure that a structural failure in a payload would not compromise the Space Shuttle or its Orbiter. NASA classified payloads by the nature of their safety criticality. Typically, a standard fracture criticality classification process started by removing all exempt parts that were nonstructural items—i.e., items not susceptible to crack propagation such as insulation blankets or certain common small parts with well-developed quality-control programs and use history.

All remaining parts were then assessed as to whether they could be classified as non-fracture critical. This category included the following classifications:

■ Low-released mass—parts with a mass low enough that, if released during a launch or landing, would cause no damage to other components

■ Contained—a failed part confined in a container or otherwise restrained from free release

■ Fail-safe—structurally redundant designs where remaining components could adequately and safely sustain the loading that the failed member would have carried or failure would not result in a catastrophic event

■ Low risk—parts with large structural margins or other conditions making crack propagation extremely unlikely

- Nonhazardous leak-before-burst—pressure vessels that did not contain a hazardous fluid where loss of fluid would not cause a catastrophic hazard such as loss of vehicle and crew, and where the critical crack size was much greater than the vessel wall thickness

NASA processed non-fracture critical components under conventional aerospace industry verification and quality assurance procedures.

All parts that could not be classified as exempt or non-fracture critical were classified as fracture critical. Fracture critical components had to have their damage tolerance demonstrated by testing or by analysis. To assure conservative results, such tests or analyses assumed that a flaw was located in the most unfavorable location and was subjected to the most unfavorable loads. The size of the assumed flaw was based on the nondestructive inspections that were used to inspect the hardware. The tests or analyses had to demonstrate that such an assumed crack would not propagate to failure within four service lifetimes.

Fracture Control Software Development

Few analytical tools were available for fracture mechanics analysis at the start of the Space Shuttle Program. The number of available analytical solutions was limited to a few idealized crack and loading configurations, and information on material dependency was scarce. Certainly, computing power and availability provided no comparison to what eventually became available to engineers. Improved tools to effect the expanded application of fracture mechanics and fracture control were deemed necessary for safe operation of the shuttle.

With Space Shuttle Program support, Johnson Space Center (JSC) initiated a concerted effort in the mid 1970s to create a comprehensive database of materials fracture properties. This involved testing virtually all metallic materials in use in the program for their fracture toughness, environmental crack growth thresholds, and fatigue crack growth rate properties. NASA manufactured and tested specimens in the environments that Space Shuttle components experienced—cryogenic, room, and elevated temperatures as well as in vacuum, low- and high-humidity air, and selected gaseous or fluid environments. Simultaneously, a parallel program created a comprehensive library of analytical solutions. This involved compiling the small number of known solutions from various sources as well as the arduous task of deriving new ones applicable to shuttle configurations.

Fatigue Crack Computer Program

By the early 1980s, JSC engineers developed a computer program—NASA/FLAGRO—to provide fracture data and fracture analysis for crewed and uncrewed spacecraft components. NASA/FLAGRO was the first known program to contain comprehensive libraries of crack case solutions, material fracture properties, and crack propagation models. It provided the means for efficient and accurate analysis of fracture problems.

NASGRO® Becomes a Worldwide Standard in Fracture Analysis

Although NASA/FLAGRO was essentially a shuttle project, NASA eventually formed an agencywide fracture control methodology panel to standardize fracture methods and requirements across the agency and to guide the development of

**Crack Models and Material Properties Required for Fracture Analyses**
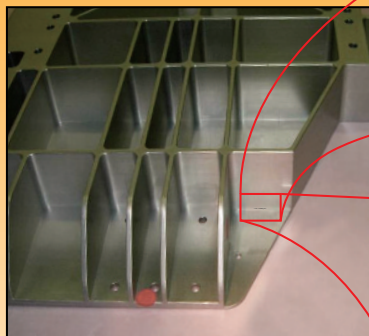
Crack in a payload mounting plate.

Fracture mechanics pretest and posttest specimens for characterizing material behavior.
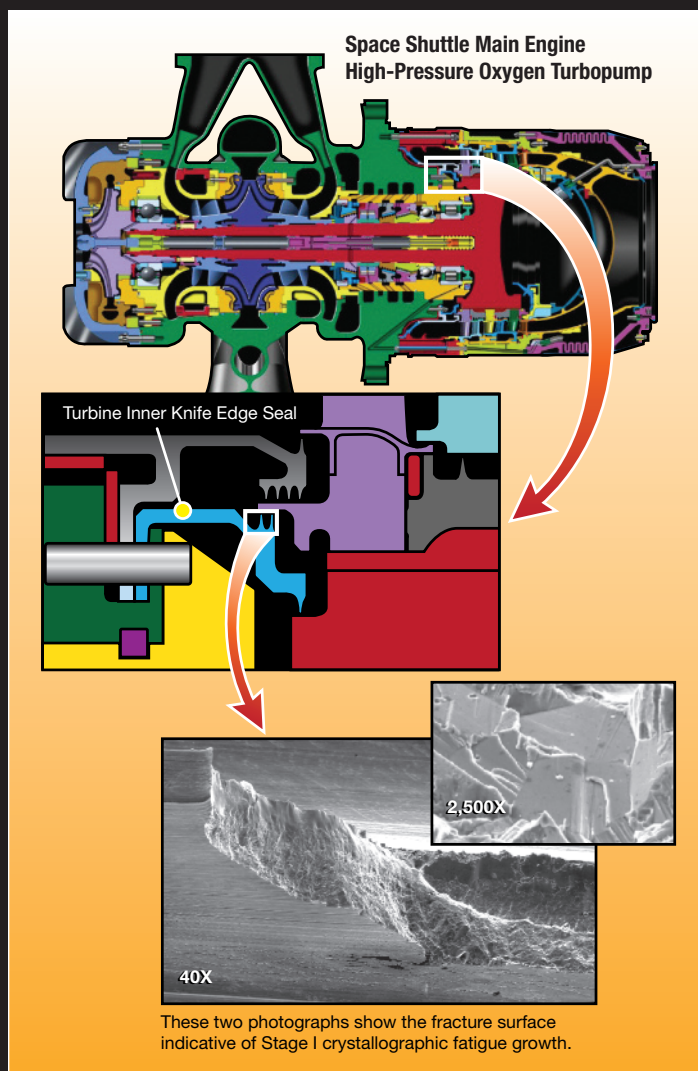
Typical NASGRO® analytical model of cracked structure for prediction of fatigue and fracture behavior, in which the crack driving force (K) is a function of the applied stress (σ) and the crack depth (a).

$$K = F\, \sigma \sqrt{\pi a}$$
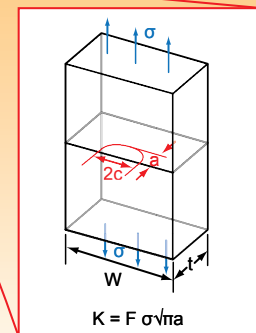
Space Shuttle Main Engine Fracture Control

The early Space Shuttle Main Engine (SSME) criteria for selecting fracture critical parts included Inconel® 718 parts that were exposed to gaseous hydrogen. These specific parts were selected because of their potential for hydrogen embrittlement and increased crack growth caused by such exposure. Other parts such as turbine disks and blades were included for their potential to produce shrapnel. Titanium parts were identified as fracture critical because of susceptibility to stress corrosion cracking. Using these early criteria, approximately 59 SSME parts involving some 290 welds were identified as being fracture critical.

By the time the alternate turbopumps were introduced into the shuttle fleet in the mid 1990s, fracture control processes had been well defined. Parts were identified as fracture critical if their failure due to cracking would result in a catastrophic event. The fracture critical parts were inspected for preexisting cracks, a fracture mechanics assessment was performed, and materials traceability, and part-specific life limits were imposed as necessary. This combination of inspection, analysis, and life limits ensured SSME fracture critical parts were flown with confidence.

Space Shuttle Main Engine High-Pressure Oxygen Turbopump

Turbine Inner Knife Edge Seal

2,500X

40X

These two photographs show the fracture surface indicative of Stage I crystallographic fatigue growth.

NASA/FLAGRO, renamed NASGRO®, for partnership with industry. While other commercial computer programs existed by the end of the Space Shuttle Program, none had approached NASGRO® in its breadth of technical capabilities, the size of its fracture solution library, and the size of its materials database. In addition to gaining several prestigious engineering awards, NASGRO® is in use by organizations and companies around the world.

Summary

Fracture mechanics is a technical discipline first used in the Apollo Program, yet it really came of age in the Space Shuttle Program. Although there is still much to be learned, NASA made great strides in the intervening 4 decades of the shuttle era in understanding the physics of fracture and the methodology of fracture control. It was this agency's need to analyze shuttle and payload fracture critical structural hardware that led to the development of fracture mechanics as a tool in fracture control and ultimately to the development of NASGRO®— the internationally recognized fracture mechanics analysis software tool. The shuttle was not only a principal benefactor of the development of fracture control, it was also the principal sponsor of its development.